The Keck Interferometer (Nuller)

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The People Involved

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Outline

- The Keck Interferometer
- Keck Science → Nulling Science
- Symmetric Nullers
- The Keck Interferometer Nuller

Keck Interferometer

- Interferometry with the two 10-m Keck telescopes
- NASA-funded joint project between JPL and CARA
- Broad range of science capabilities
- Precursor interferometry work to SIM and TPF

Key Features

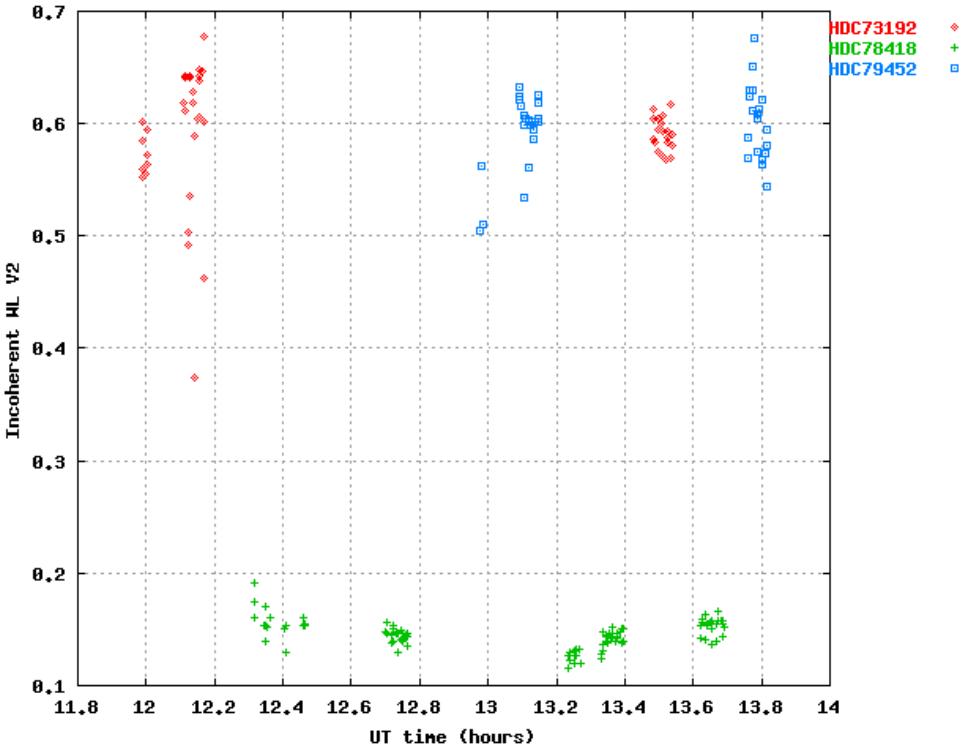
- Michelson combination among two 10-m Kecks on 85 m baseline
- Telescope phasing with adaptive optics (S = 98% at N band) and fast tip/tilt correction
- Interferometer cophasing with NIR fringe tracking & active delay lines
  - Dual-star/dual-subaperture feeds at each telescope
- Back-end instruments:
  - Two-way beam combiners at 1.5--2.4 μm for fringe tracking (cophasing), V^2 observations (potentially astrometry & imaging)
  - Nulling beam combiner at 10 μm
  - Two-way combiner for differential phase at 2-4 μm
  - Imaging combiner at 1.6--5 μm

Keck Interferometer Science

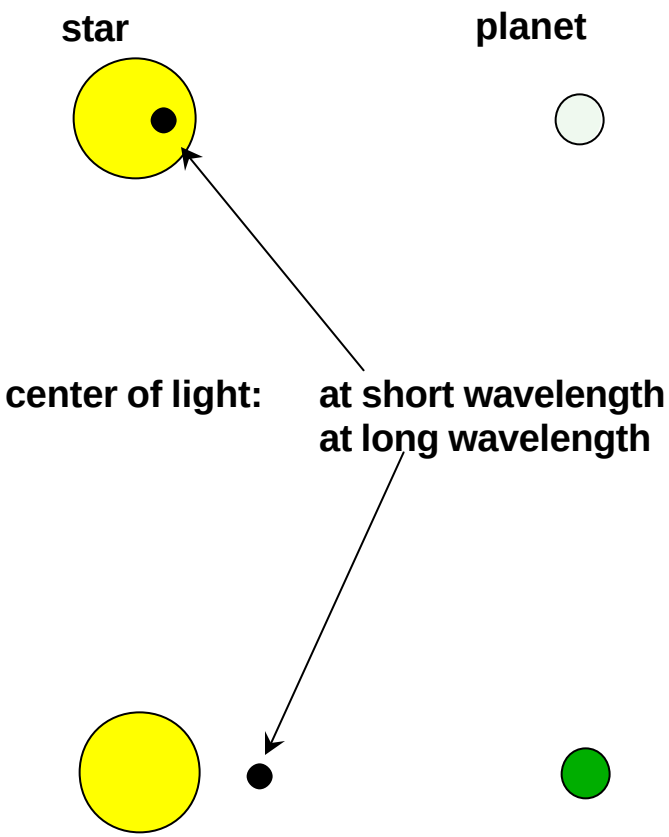
- Science with the two Kecks
  - Measurement of exozodiacal dust using nulling
  - Detection of hot Jupiters using differential phase
  - High sensitivity parametric imaging
- Science with the Kecks and the proposed outriggers
  - Astrometric search for planets
  - Imaging with 4, 5 , or 6-element array

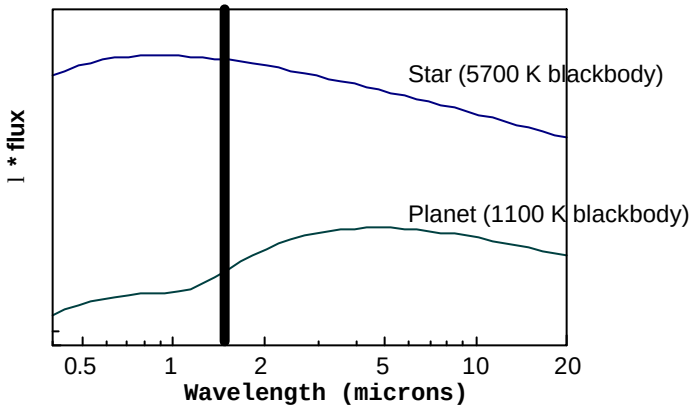
Keck V^2 Results

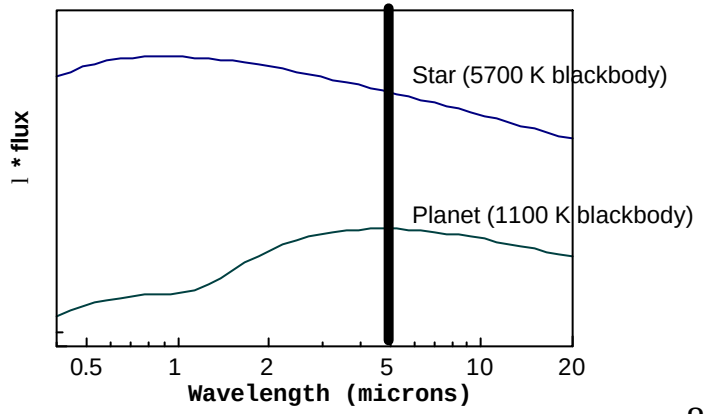
- Binary previously observed with PTI (known orbit): 75 Cnc (HD 78418) in partly cloudy weather
- In good weather, rms V^2 is about 5%
- Have locked fringes to K=8.6 stars with 2 ms scan
- Successful operation with 5 ms scan
- Papers on HL Tau and NGC 4151 out



Detection of Hot Jupiters with Differential Phase

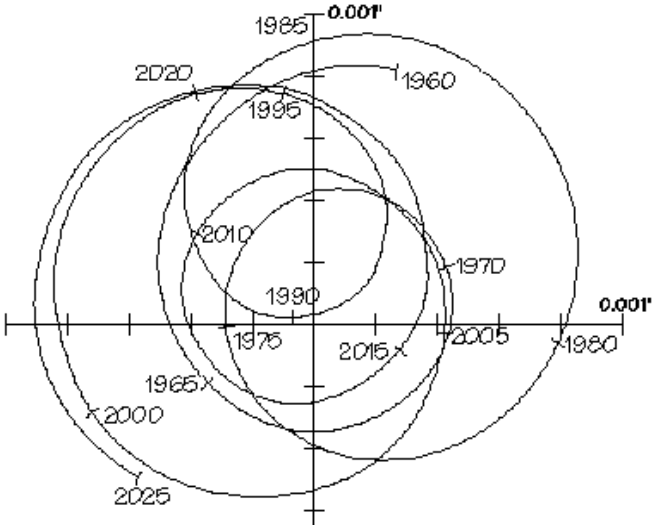






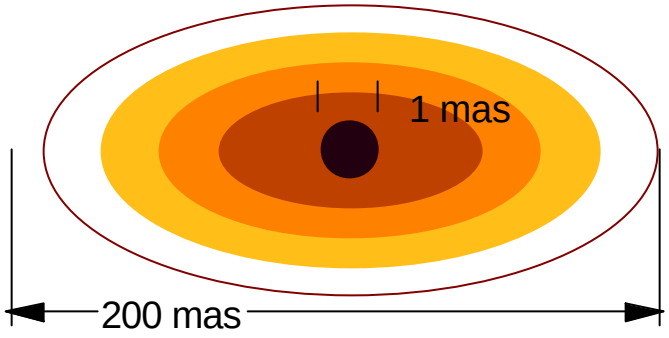
Astrometric Detection of Exoplanets

- Science objective
  - Survey 100's of nearby stars for planets to Uranus mass
  - Would use proposed outrigger telescopes for long-term survey
- Proposed approach
  - High-accuracy narrow-angle astrometry
  - Orthogonal >100m baselines; dual-star feeds
  - 30 μas per hour accuracy for differential astrometry

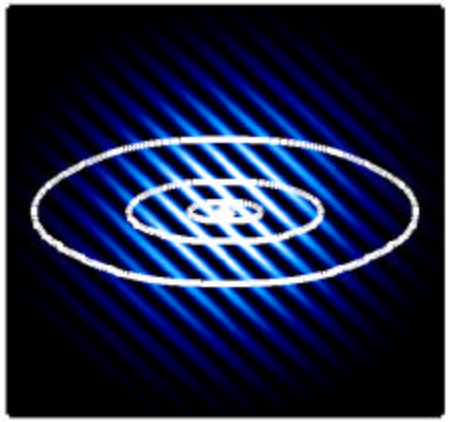


Measurement of Exozodiacal Dust with Nulling

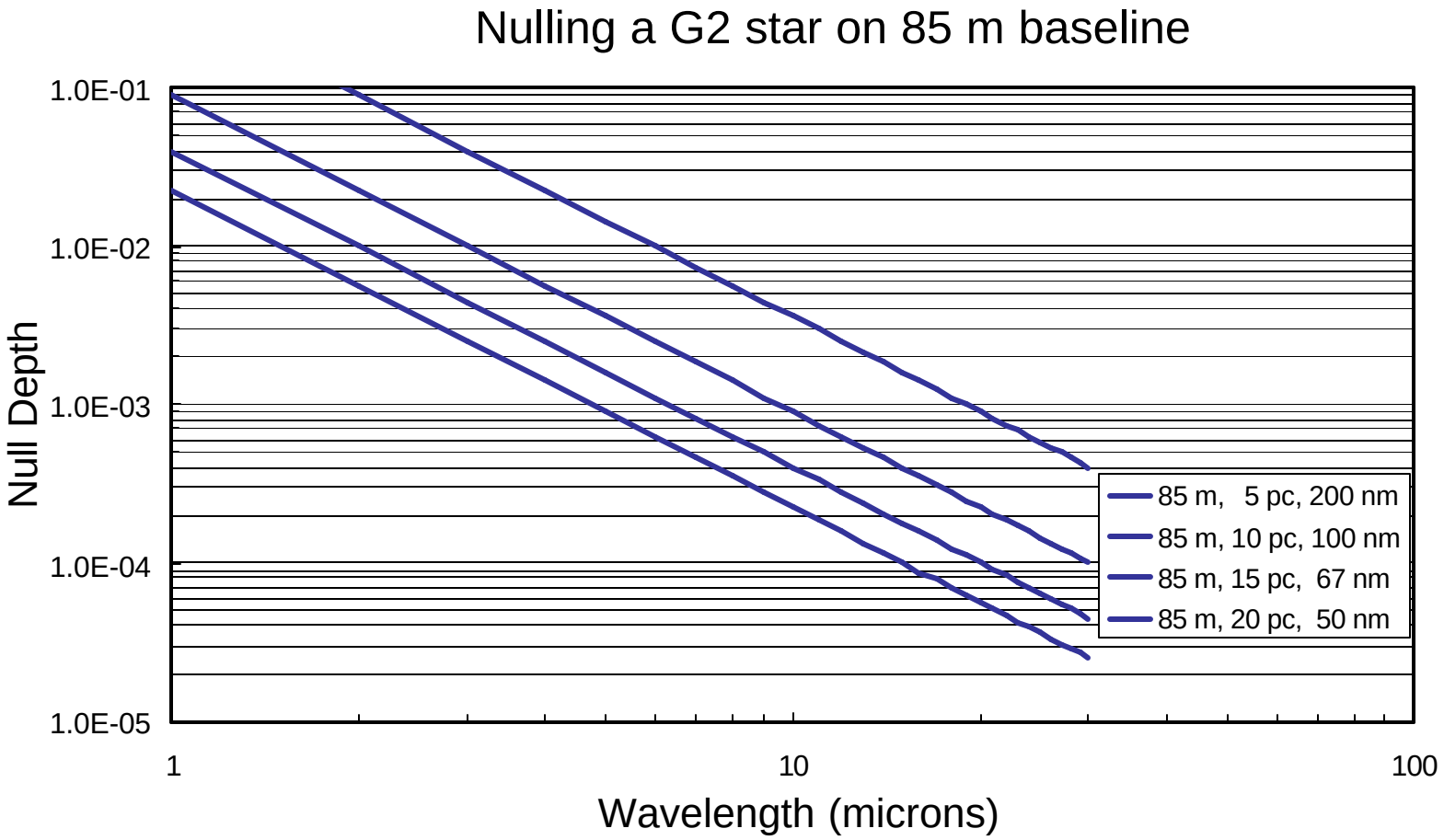
- Characterization of the exozodiacal emission around nearby stars as a preliminary to TPF
  - Goal: detection of a 10-solar-system equivalent zodiacal dust disk (10^{-3} of star)
- Features of the measurement
  - Strong light from central star
  - Relatively weak exozodiacal signal
  - Strong 10-μm background
- Two nuller scales at 10 μm
  - Aperture:
    λ / diameter = 400 mas
  - Interferometer:
    λ / baseline = 25 mas



1AU radius disk at 10 pc

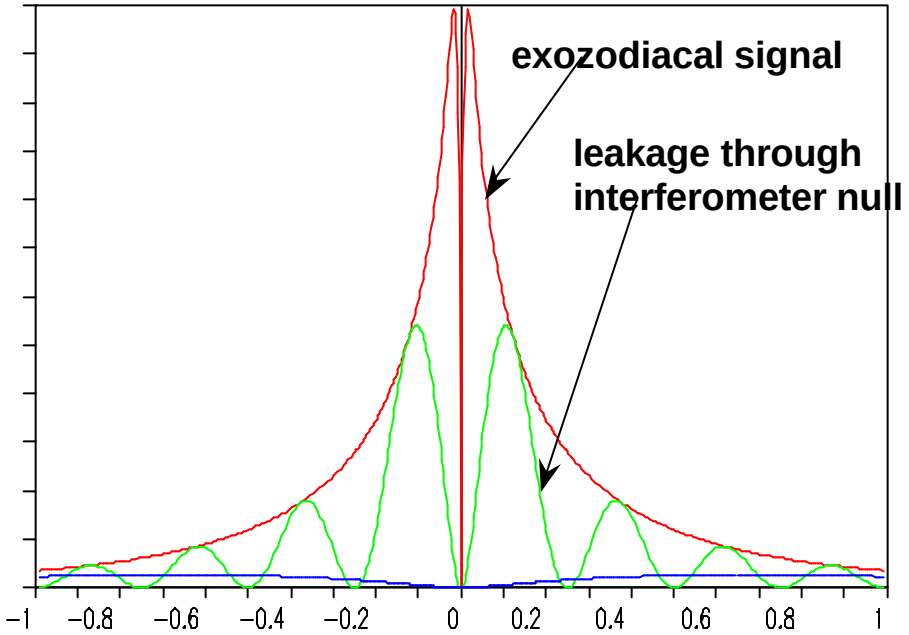


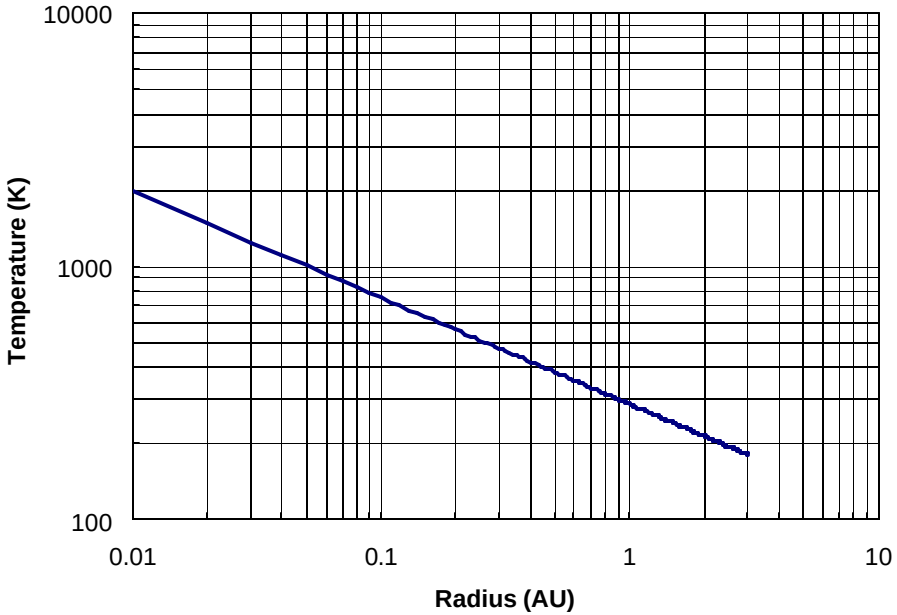
Stellar null depths vs. wavelength, and required phase accuracy



To achieve the baseline-limited null, require: $\sigma_x < b\theta_d/4$

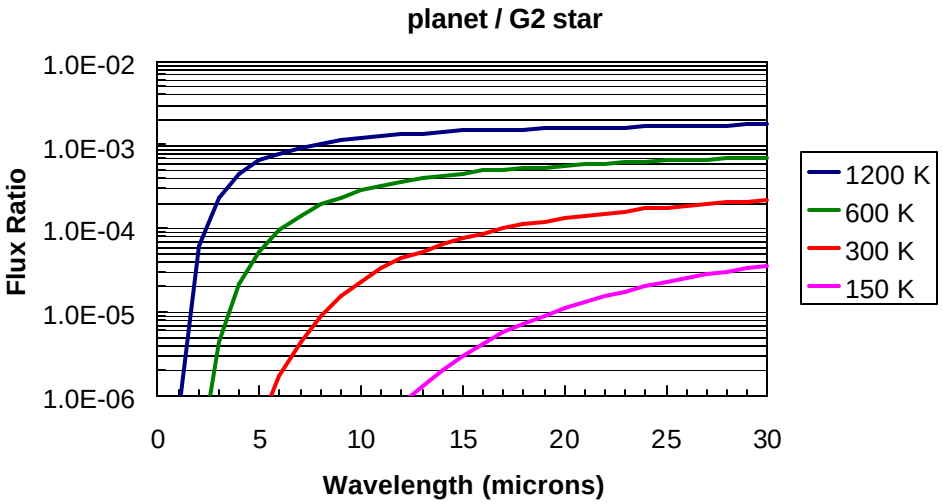
Sensitivity of the Keck Nuller to Exozodiacal Light

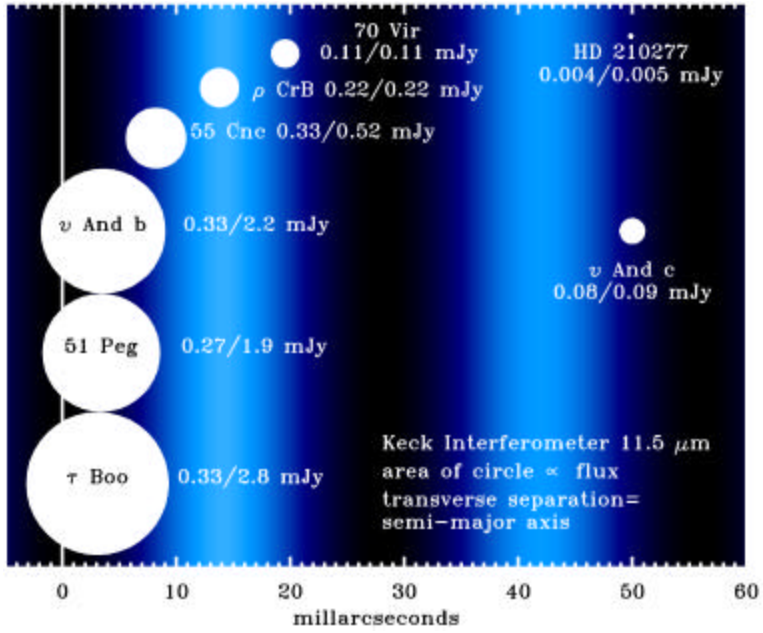




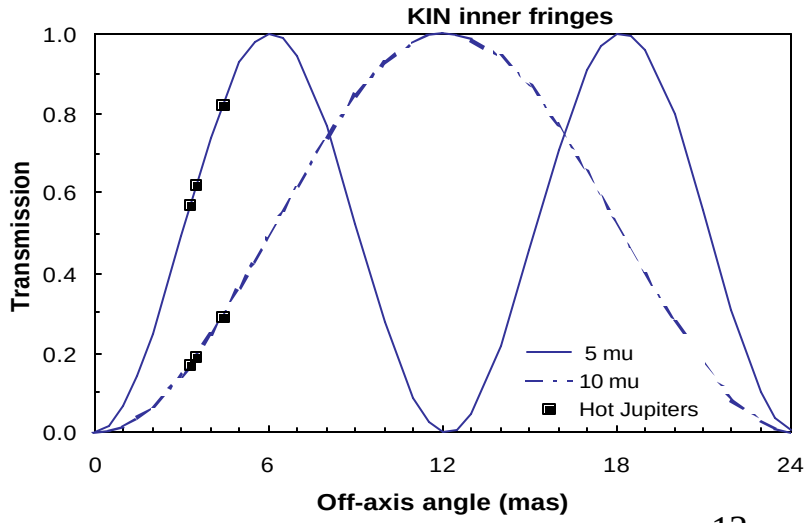
			total flux		KI fluxes		Zodis for SNR = 5			
	star	**model**	uJy	Edge-On	Face-On	Edge-On	noise in 5 hrs:		17	uJy
Test				perp		par				
1	G2 @ 10pc	a) full zodi	120.0	47.7	45.6	36.4	1.8	1.9	2.3	
2	(1 L_*)	b) cutoff at 1AU	90.0	38.2	39.2	27.0	2.2	2.2	3.2	
3		c) hole at 1AU	32.0	9.4	6.4	9.4	9.0	13.2	9.0	

Hot planets with nulling from the ground?





- First fringe maximum: $\theta_{max} = \lambda/2b$
- Equilibrium temp. there: $T \approx 300\ (b_{10}/d_{10}\lambda_{10})^{1/2}$
- Orbital Period: $P \propto b^{-1.5}$
- Short periods and wavelengths will help!



How to null? - Symmetric Nullers

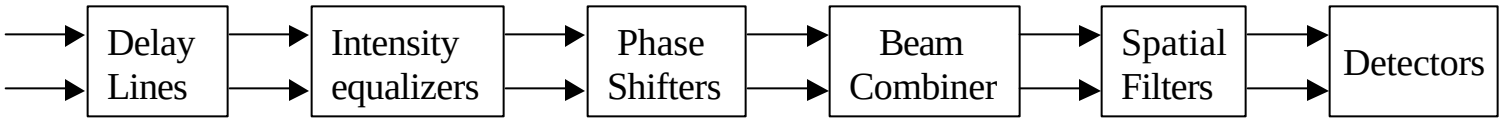
- Goal: completely symmetric, broadband, dual-polarization nuller

- Elimination of residual asymmetries:
  - Unbalanced mirror reflections
  - Asymmetric beamsplitter coating passes
  - Unequal substrate passes
  - Unequal numbers of antireflection coating passes

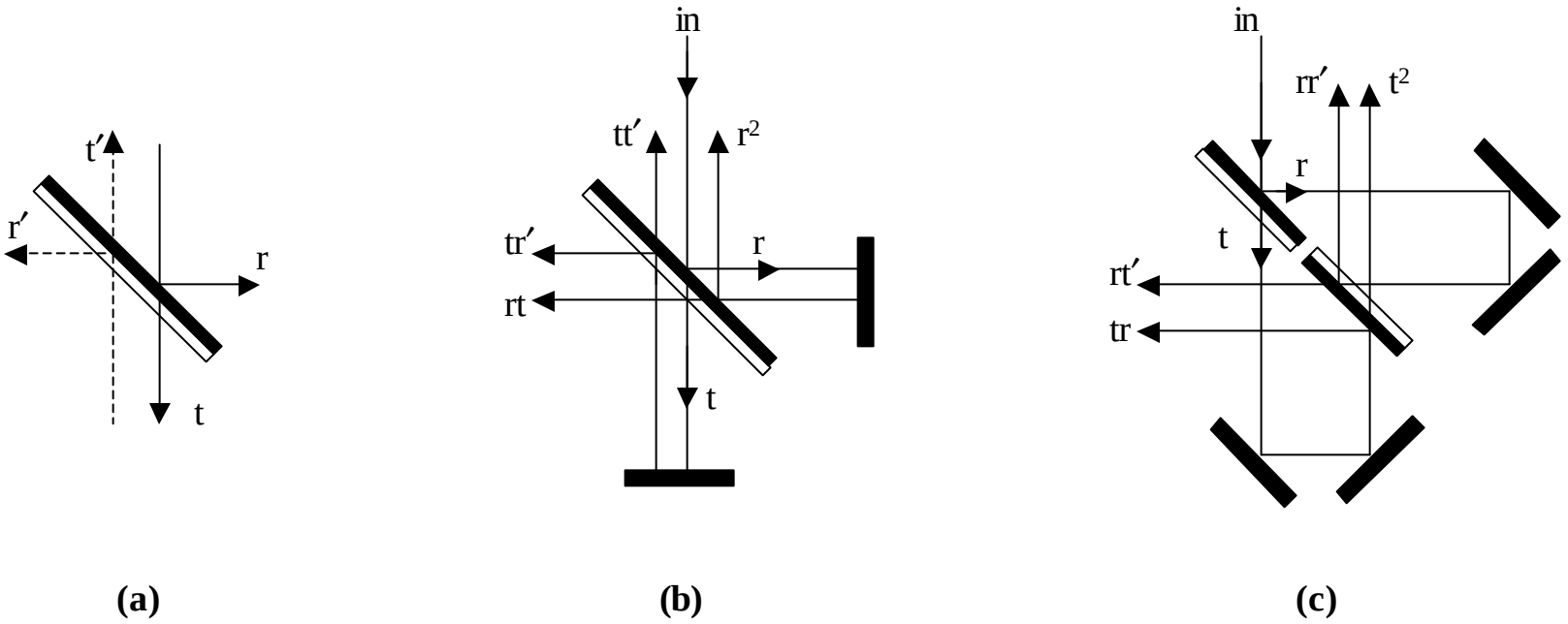
- Dual-polarization operation

- Broadband operation

- Separation of Nuller Functions:
  - Field reversal
  - Phase shifting
  - Beam combination



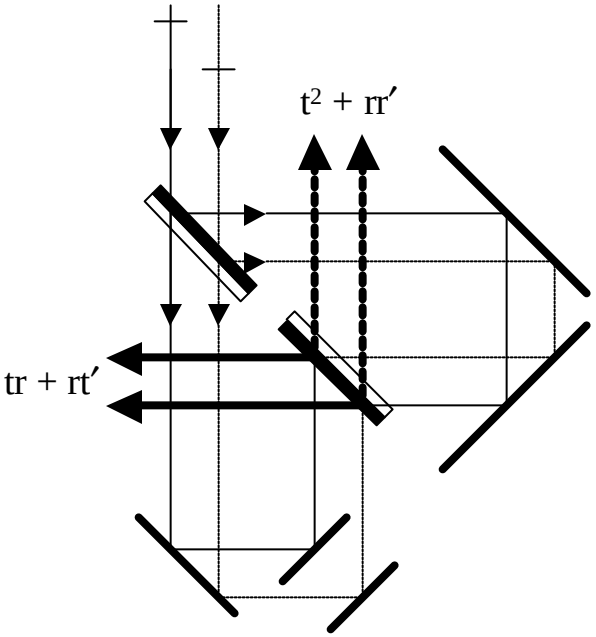
Reversed double-pass beamsplitters allow for perfect subtraction



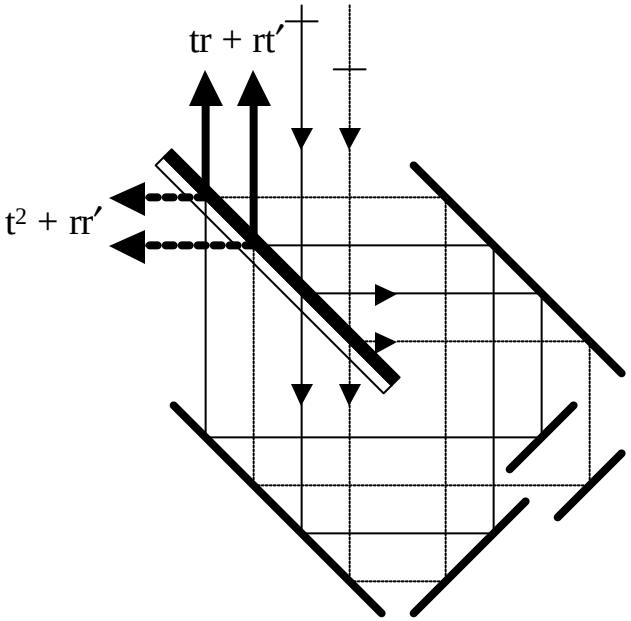
(a) **(b)** **(c)**

- Generally r ≠ t, so single pass beamsplitters are typically not symmetric
- Double pass: generally rt - r′t » 0 but not = 0, but rt′ - rt = 0 identically.
- Reversed pair of beamsplitters makes for a perfectly symmetric, constructive beam combiner
- Needs to be preceded by a symmetric field reversal
- Reversed beamsplitter pairs provide constructive interference, independent of polarization, wavelength, and angle-of-incidence

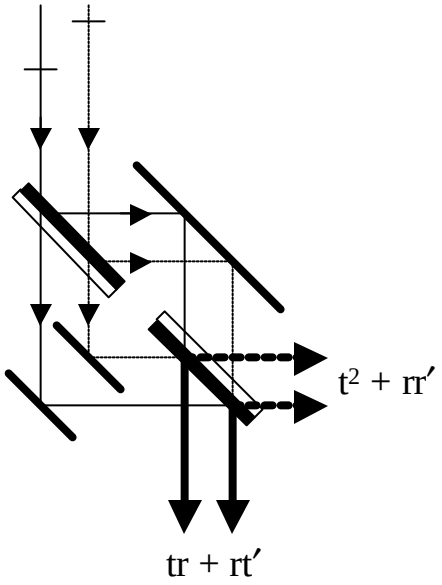
Perfectly-symmetric, constructive 2-beam combiners



Michelson

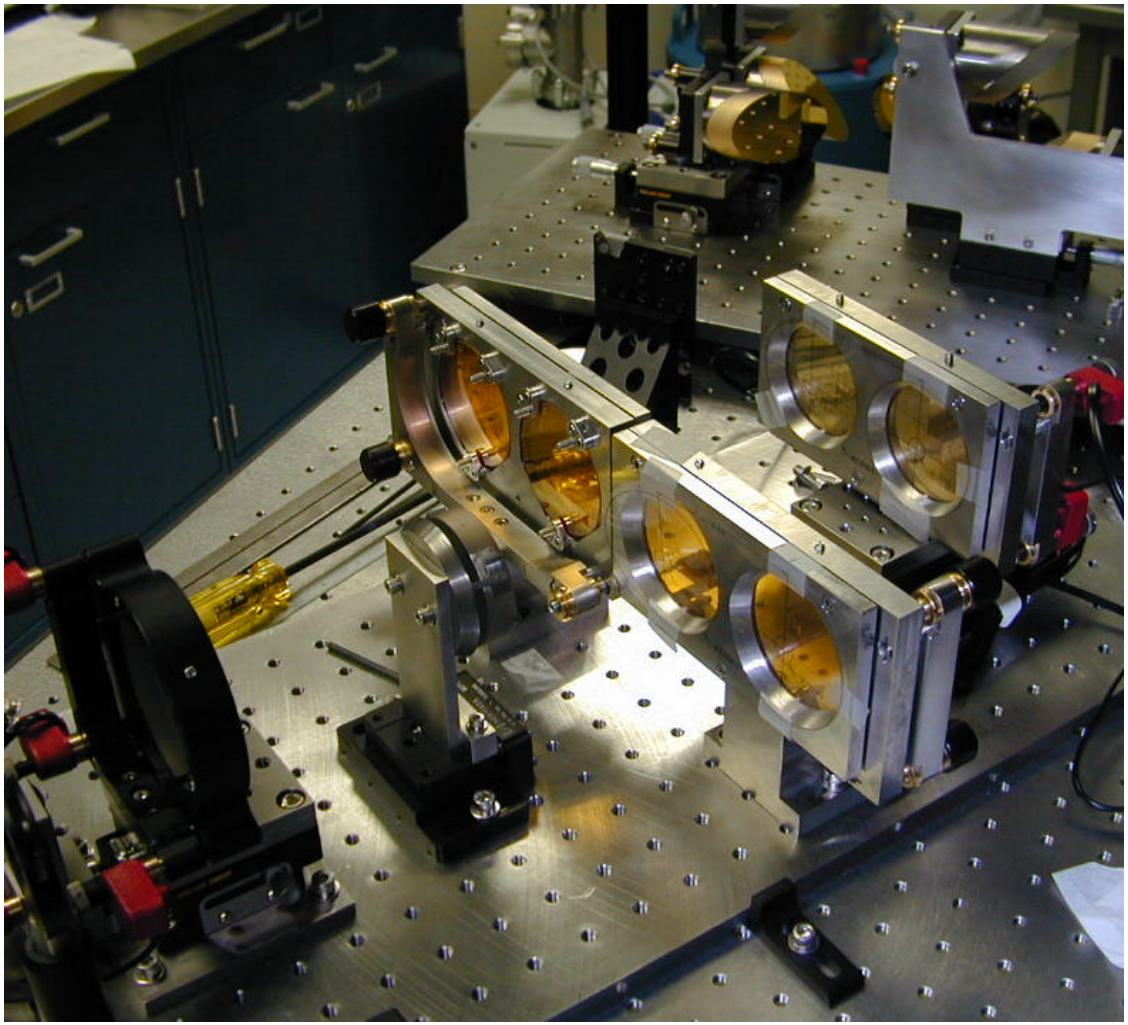


Sagnac

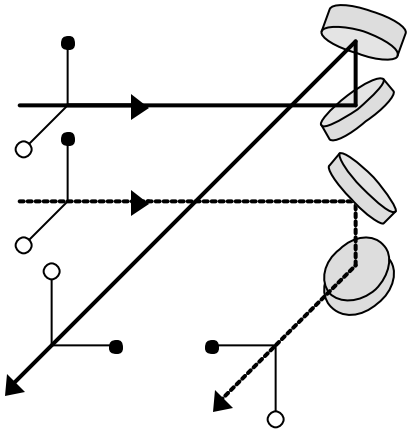


Mach-Zehnder

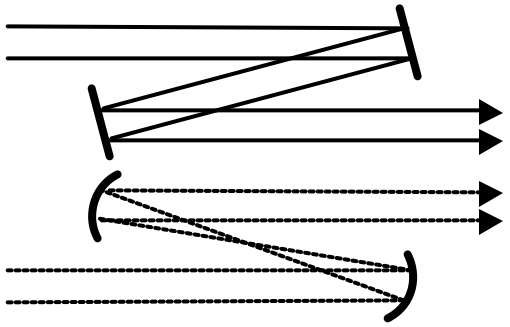
The Keck/TPF mid-infrared MMZ nullers



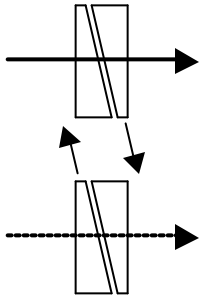
Field-reversal stages:



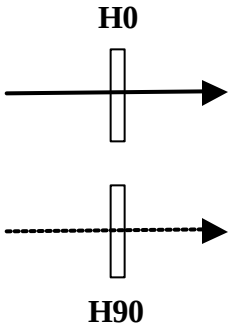
Right Angle Periscopes



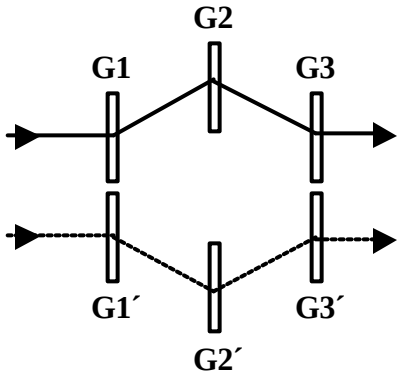
Extra Focus



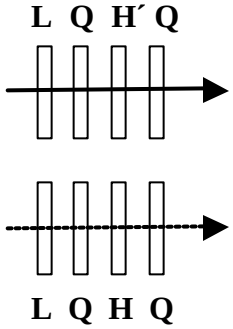
Dielectric Phase



Half Wave Plates



Grating Phase

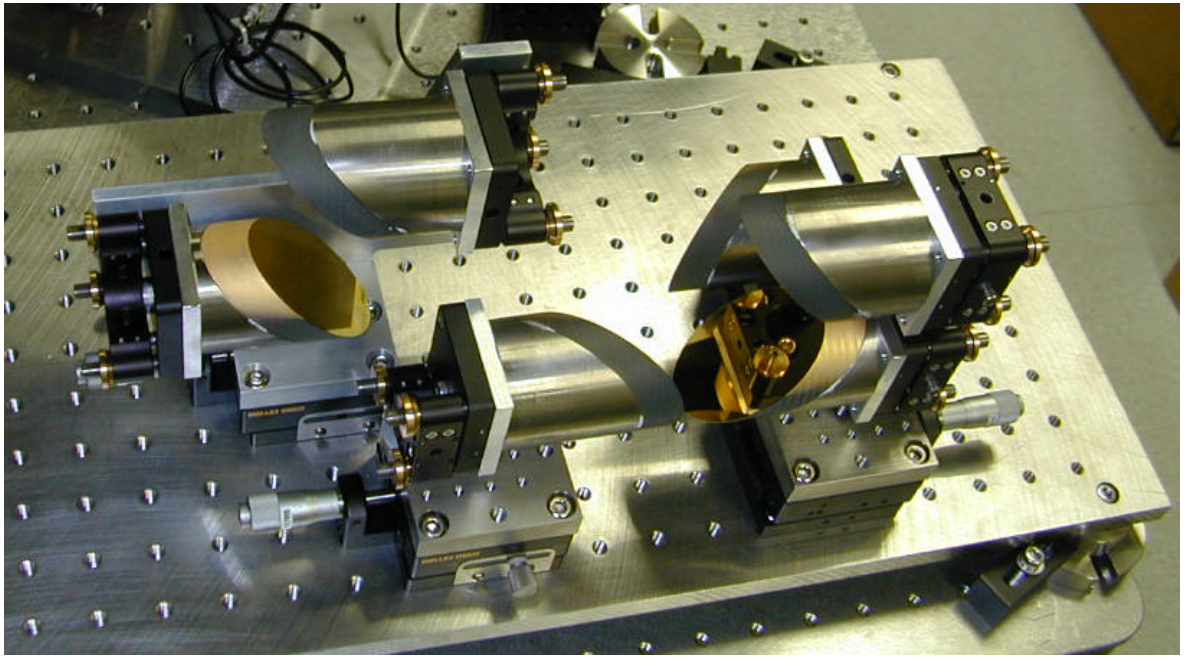


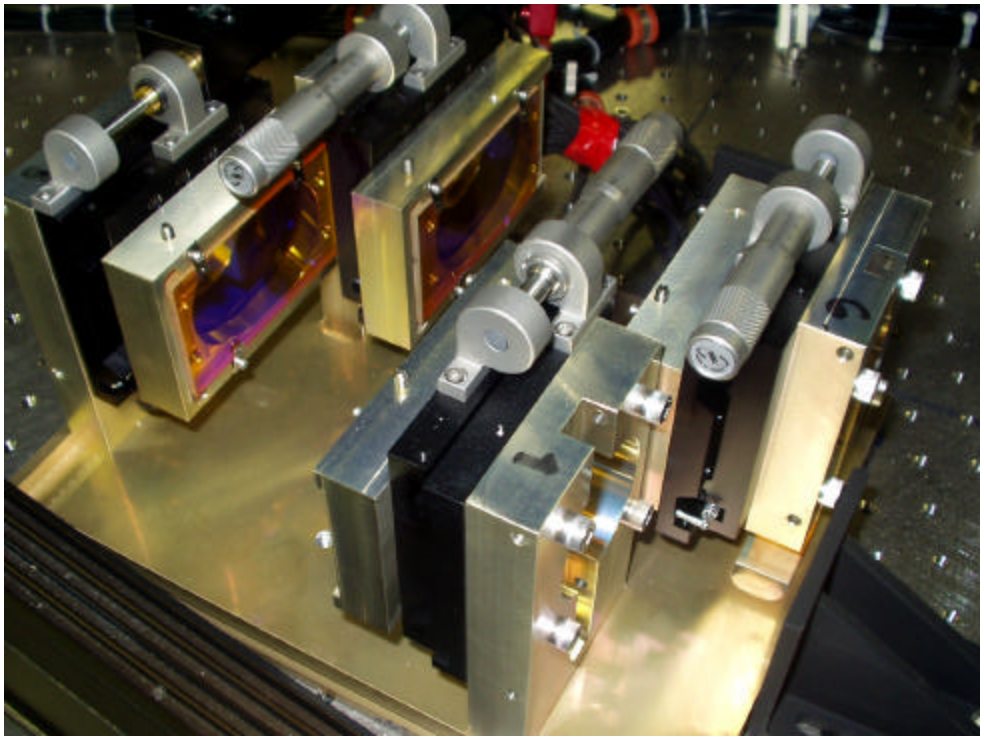
Pancharatnam Phase

- Not all fully symmetric, some are lossy; some work with single-polarization, but all could be used
- The Keck Nuller will use dielectric phase plates to counteract the atmosphere anyway, so they will be used for the nulling field flip also.

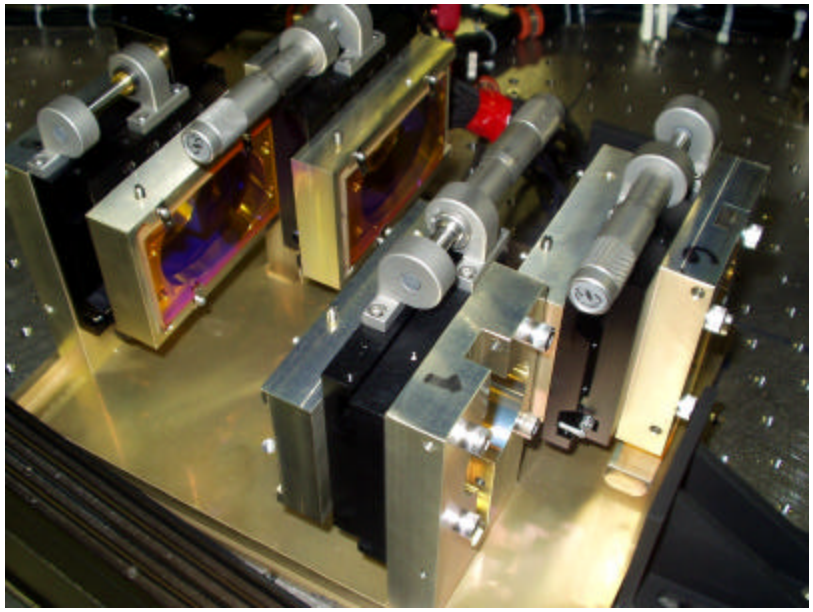
Field Flippers in the lab

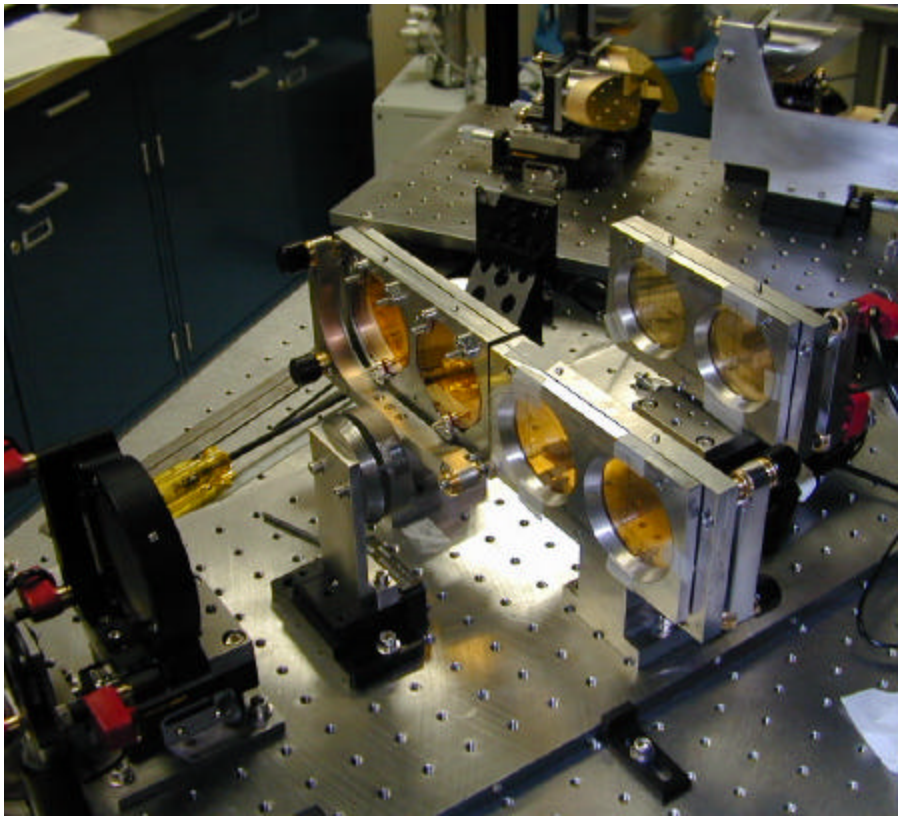
- Periscopes
- Dielectric prisms





The Keck mid-infrared MMZ nullers

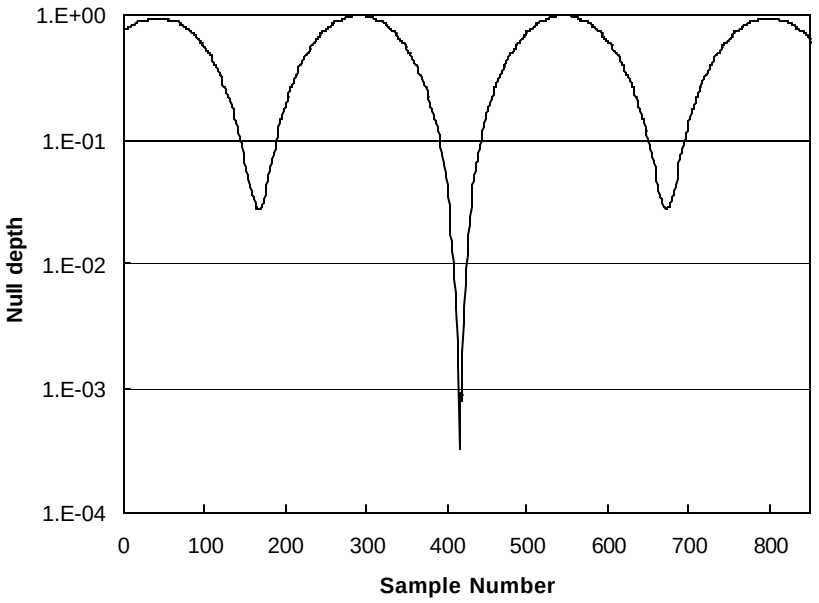


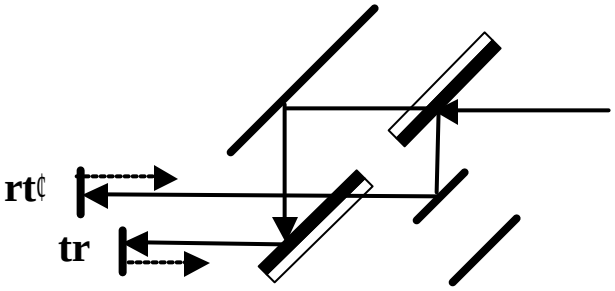


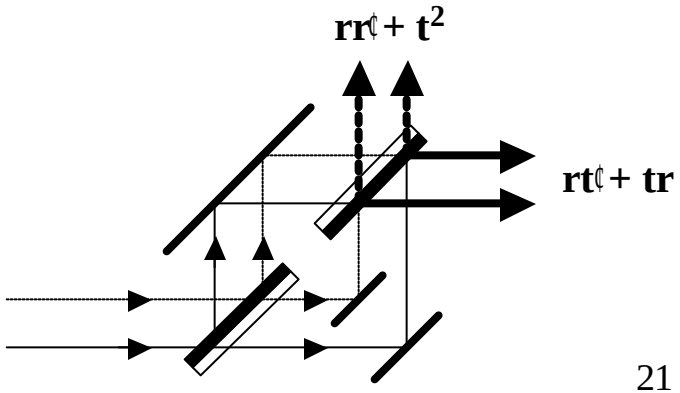
- Field reversal by dielectric plates to correct atmosphere as well
- Beam combination with MMZ

Lab results

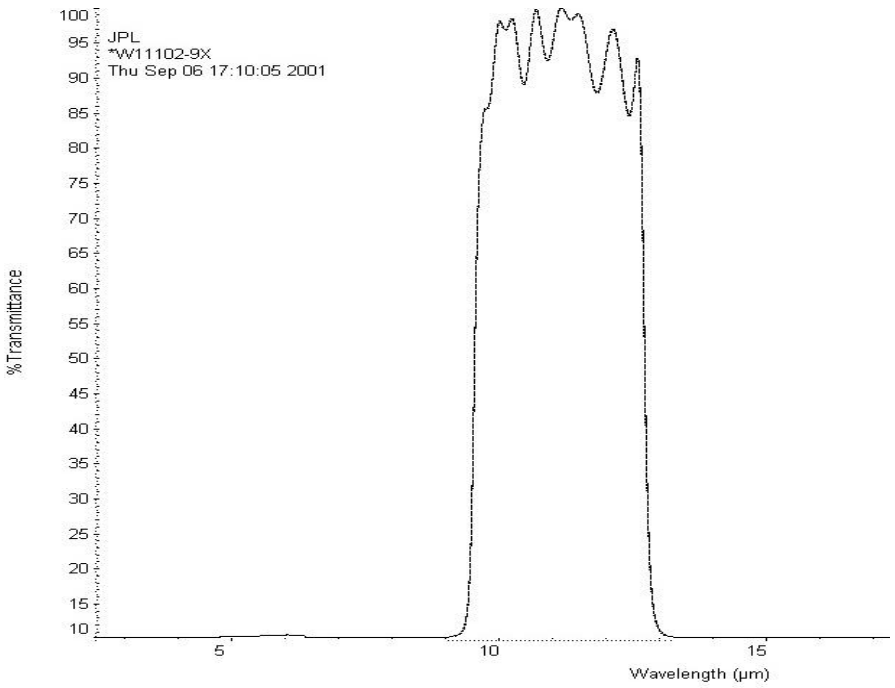
- Sources: CO_2 laser and thermal filament
- Room temperature optics
- Dielectric plate field flip and MMZ nuller
- Detector so far: single-pixel LN_2 MCT
- Single-pixel detector as the spatial filter
- Null optimization by equalization of symmetric off-center fringes
- Symmetric beams created by reverse pass through nuller
- No intensity control needed yet





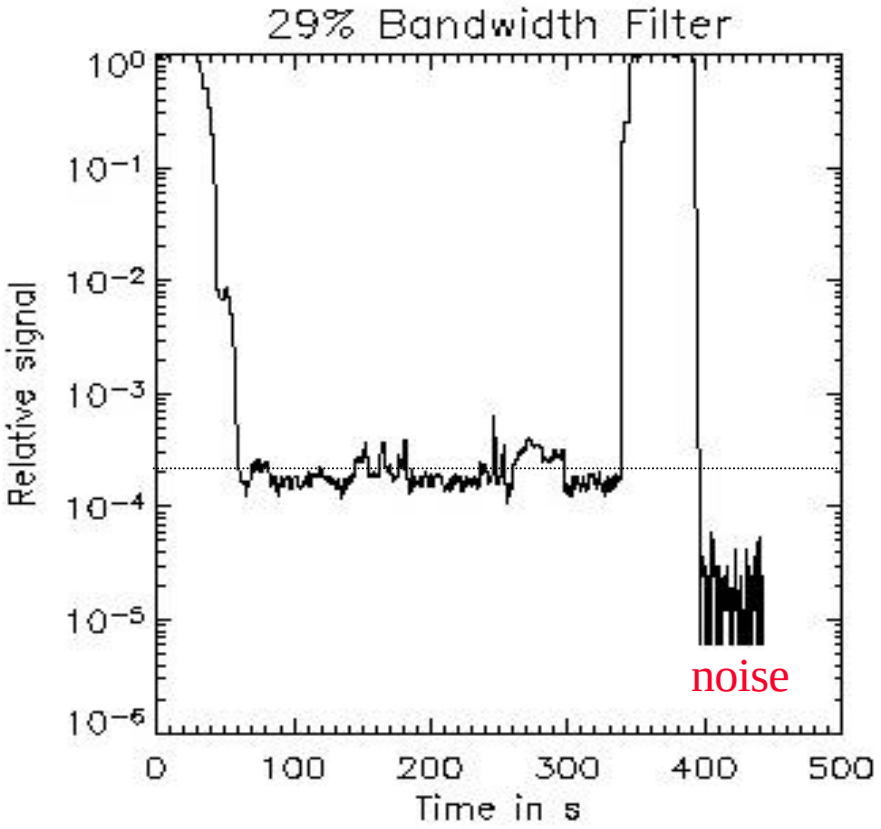


Dual Polarization non-stabilized White Light Nulls on the Keck Nuller Beam Combiner (March 24-25, 2003)



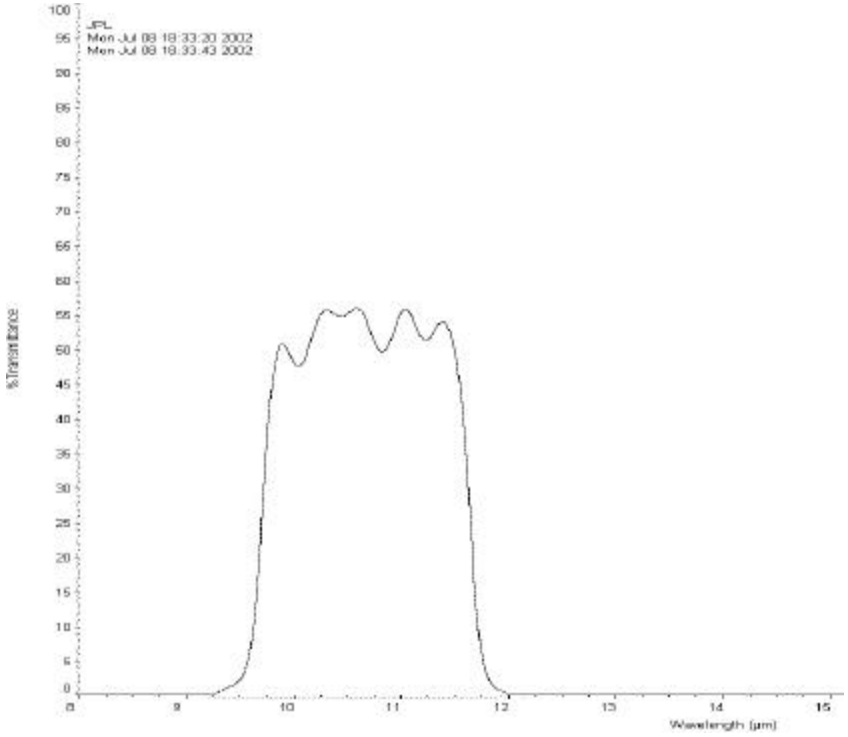
29% bandwidth filter

Half max points: 9.2-12.35 µm



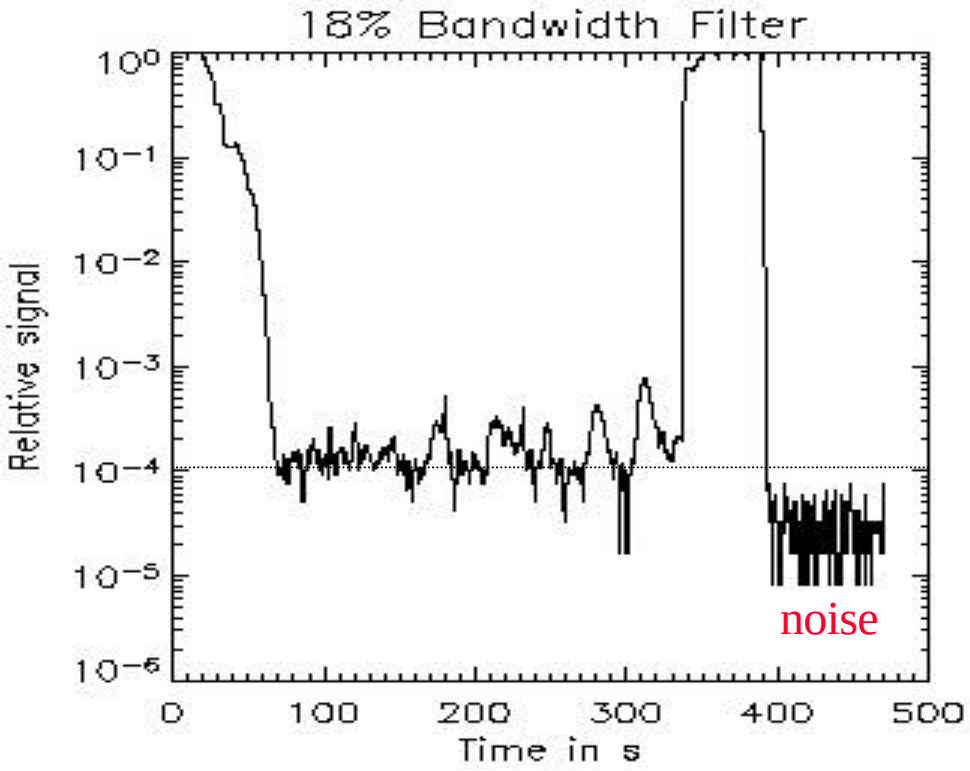
6000:1 “steady state”

Dual Polarization non-stabilized White Light Nulls on the Keck Nuller Beam Combiner (March 24-25, 2003)



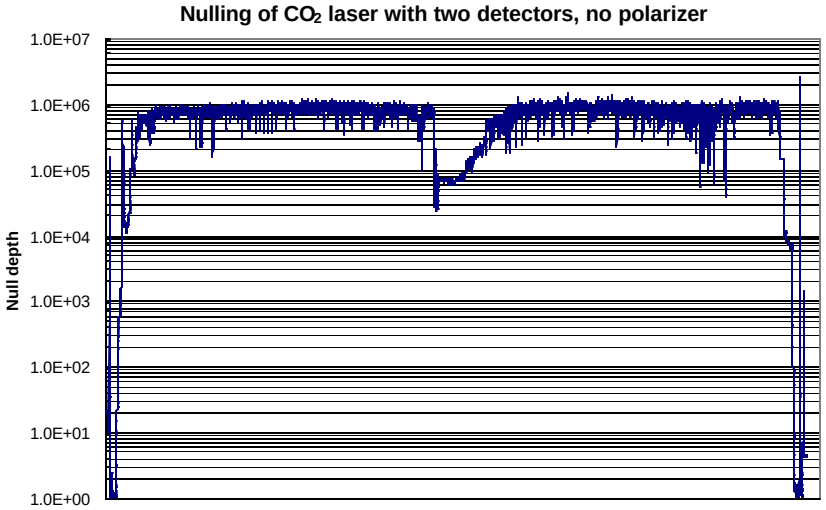
18% bandwidth

Half max points: 9.7-11.65 microns

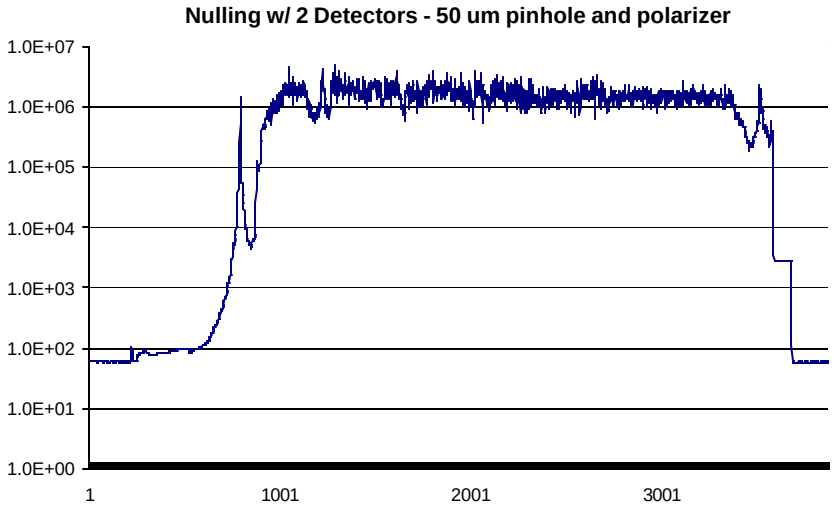


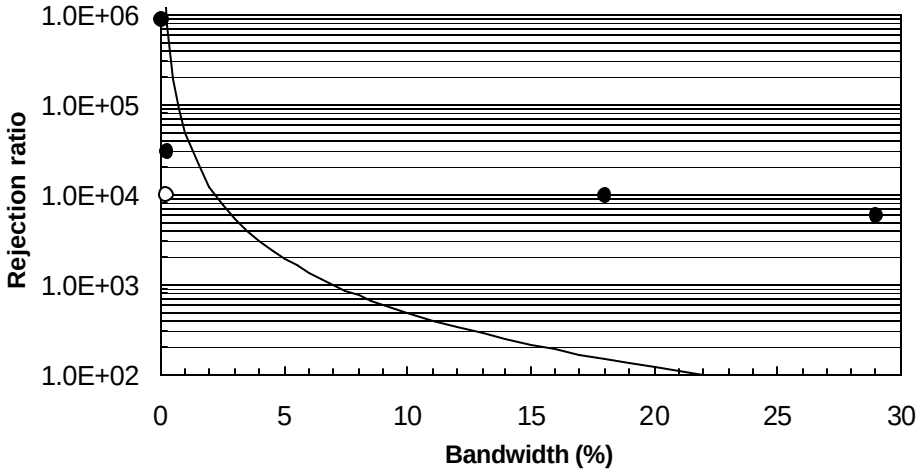
> 10,000:1 for short times

CO_2 laser nulling (TPF nuller) and summary



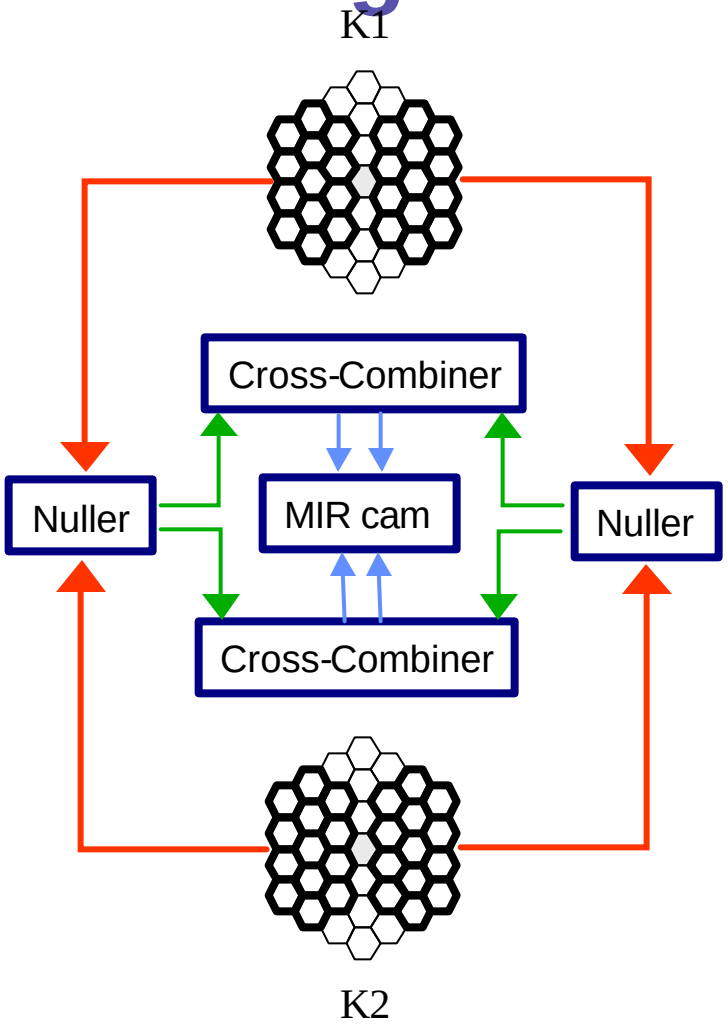
- 29% BW; no polarizers in beam, WL nulls of > 6,000:1 achieved
- 18% BW, no polarizers in beam, WL nulls of > 10,000:1 achieved
- Keck WL lab performance goal is 10,000:1 for about 20% BW
- CO_2 laser nulled to > 900,000:1 with transients past 1,000,000:1, also with no polarizers in beam





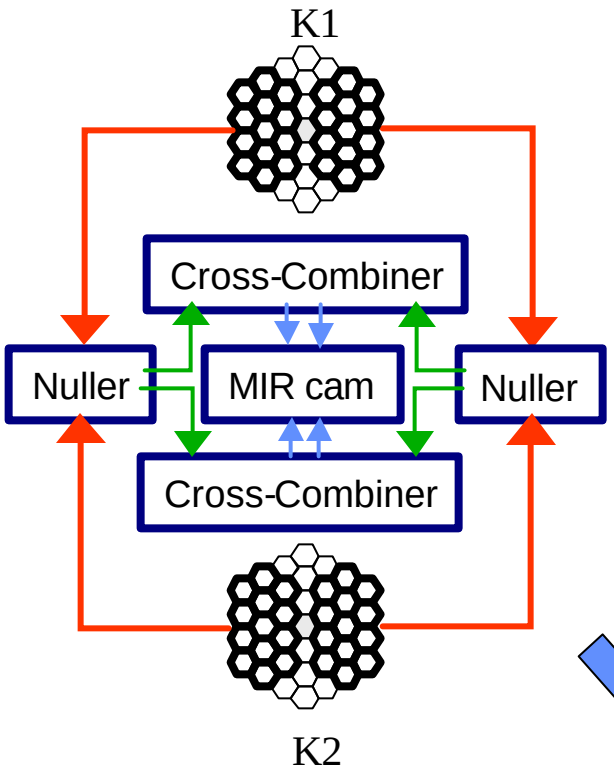
Keck System Architecture: Dual-baseline Nulling

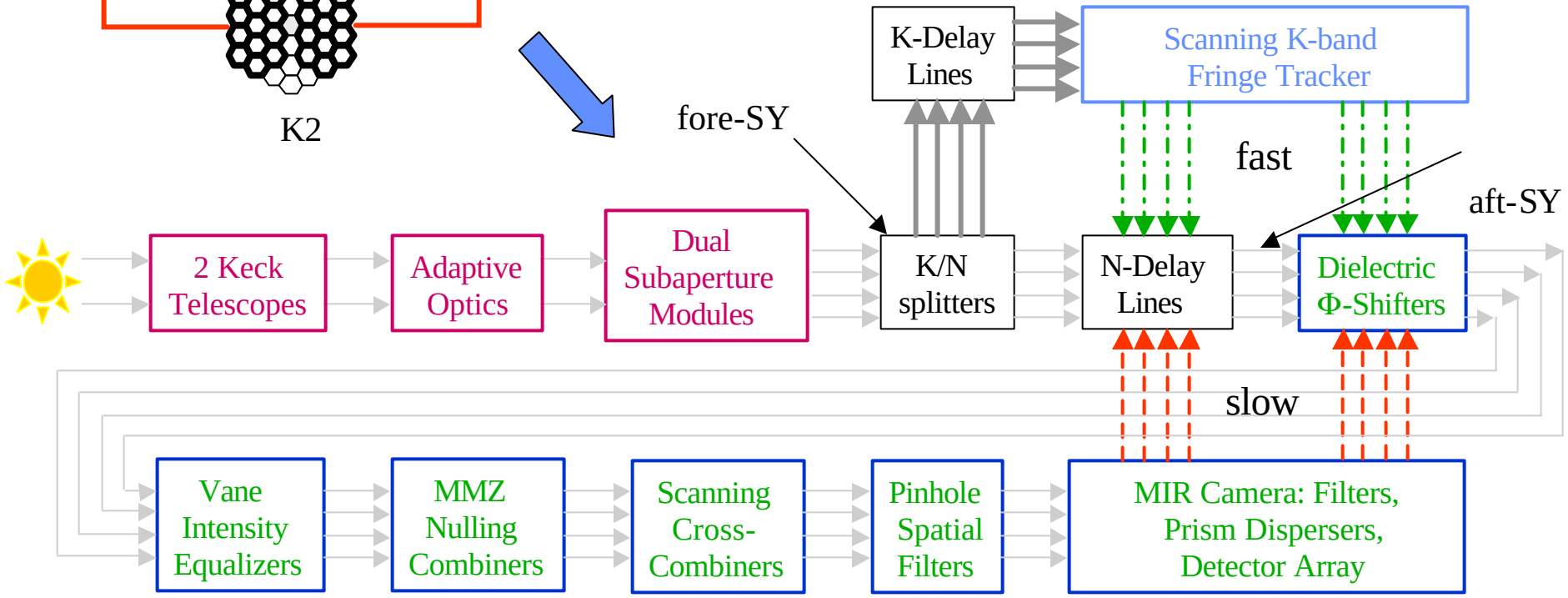
- Need to remove both star and thermal background
- Dual-baseline nulling
  - Send two beams to basement from two sup-apertures on each telescope
- Null star on each of two K1-K2 baselines
- Perform standard OPD-scan interferometry on the two nulled outputs
  - Use rapid OPD scan between the two nulled beams to measure exozodi fringe
- Hardware-wise, very similar to some proposed TPF approaches



Keck Interferometer Nuller Architecture

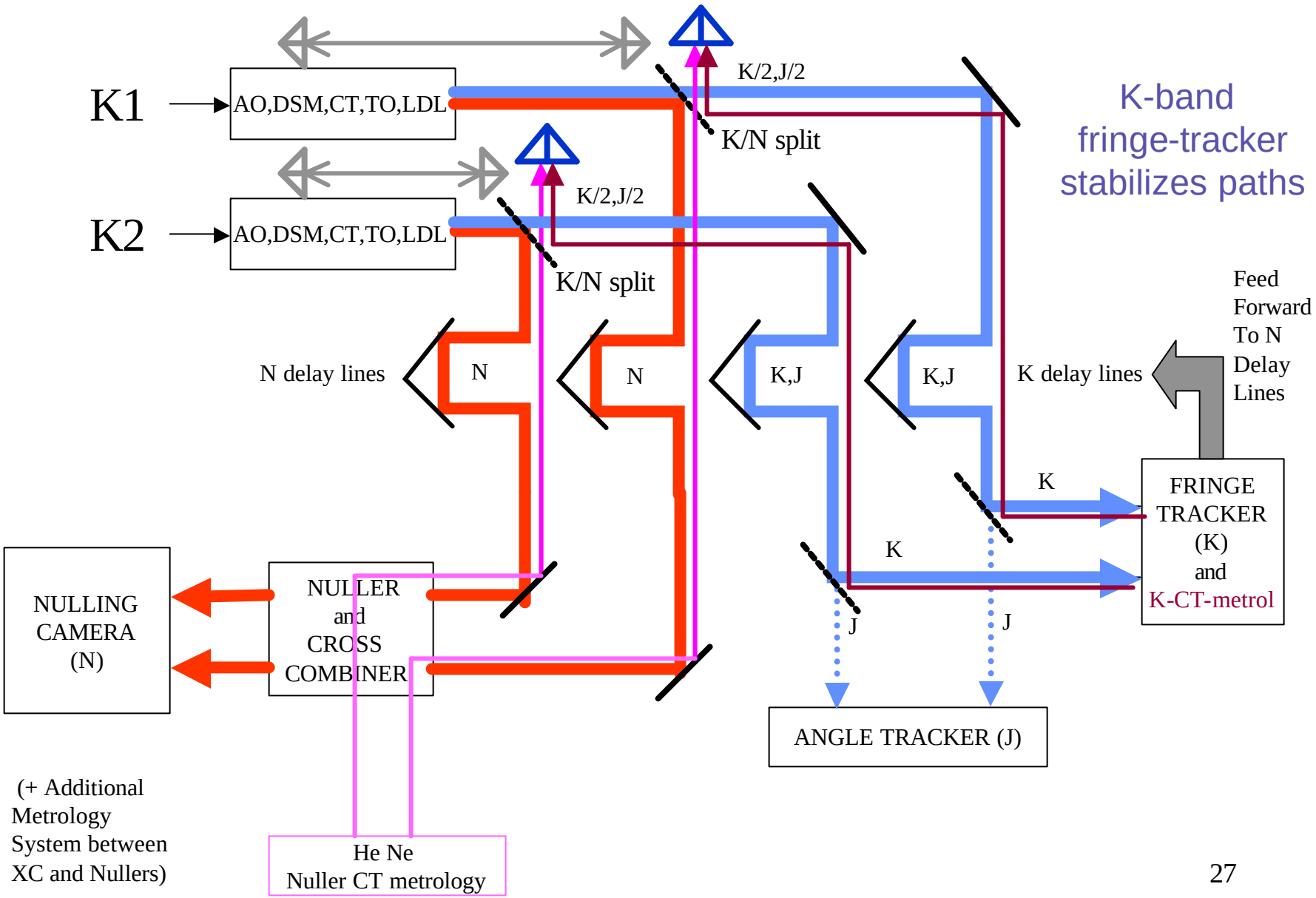
Maroon = AO bench/DSM
Black = switchyards
Green = nuller
Blue = FATCAT



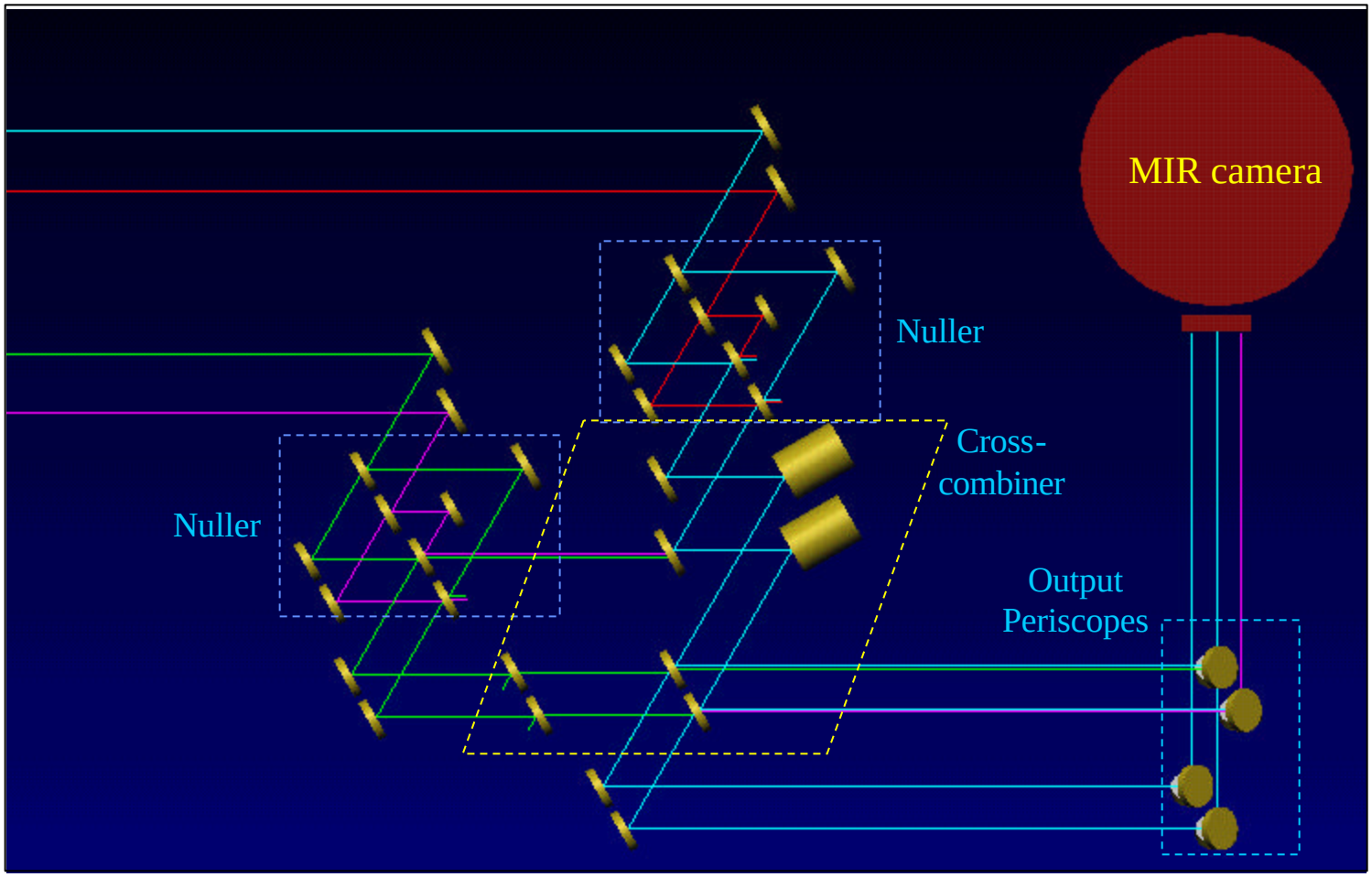


Room temperature optics prior to MIR camera

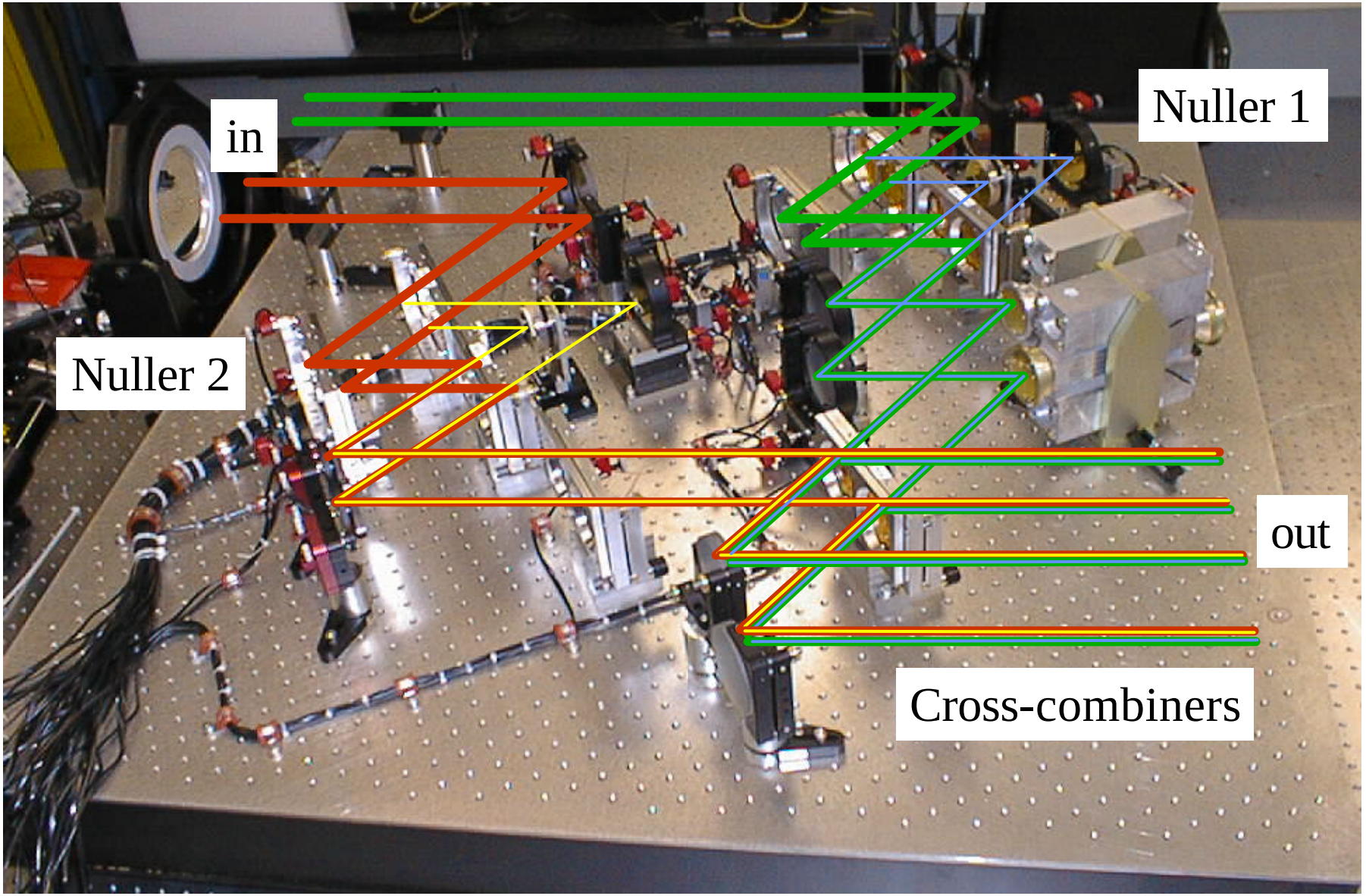
Cophasing Architecture and Metrology



Keck Nuller Optics Layout



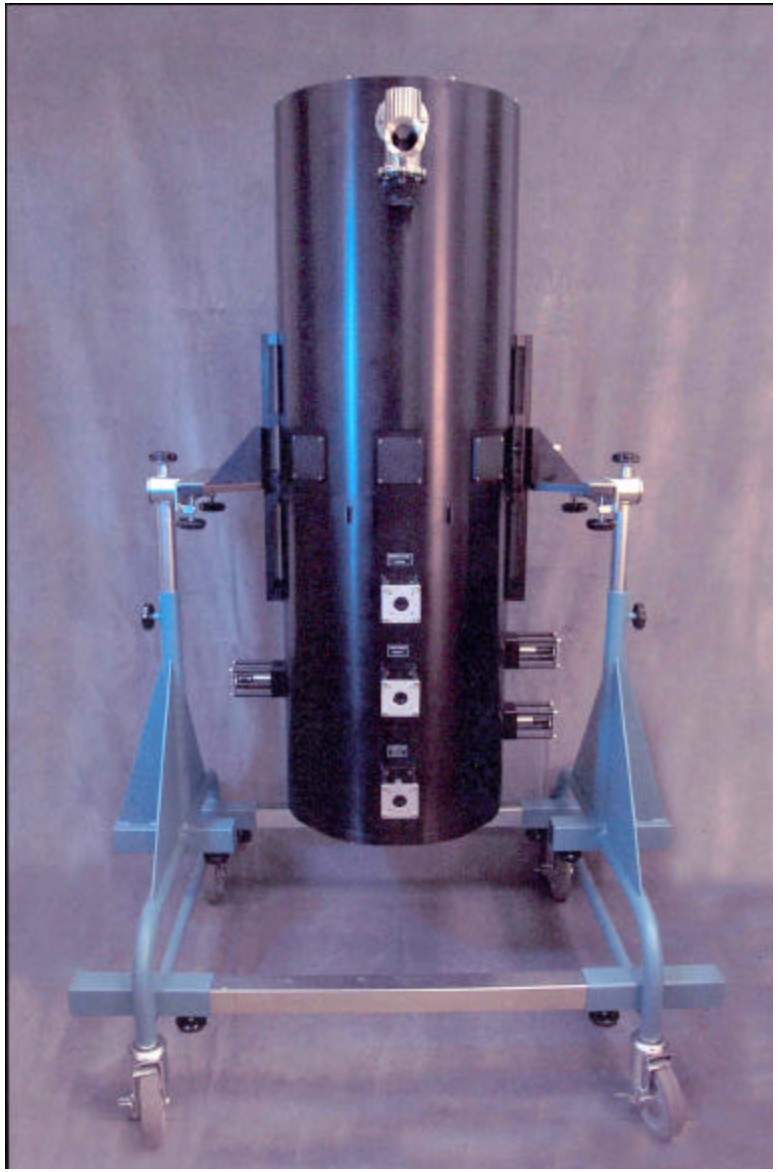
Keck nulling beam-combiner (2 nullers and 2 cross combiners)



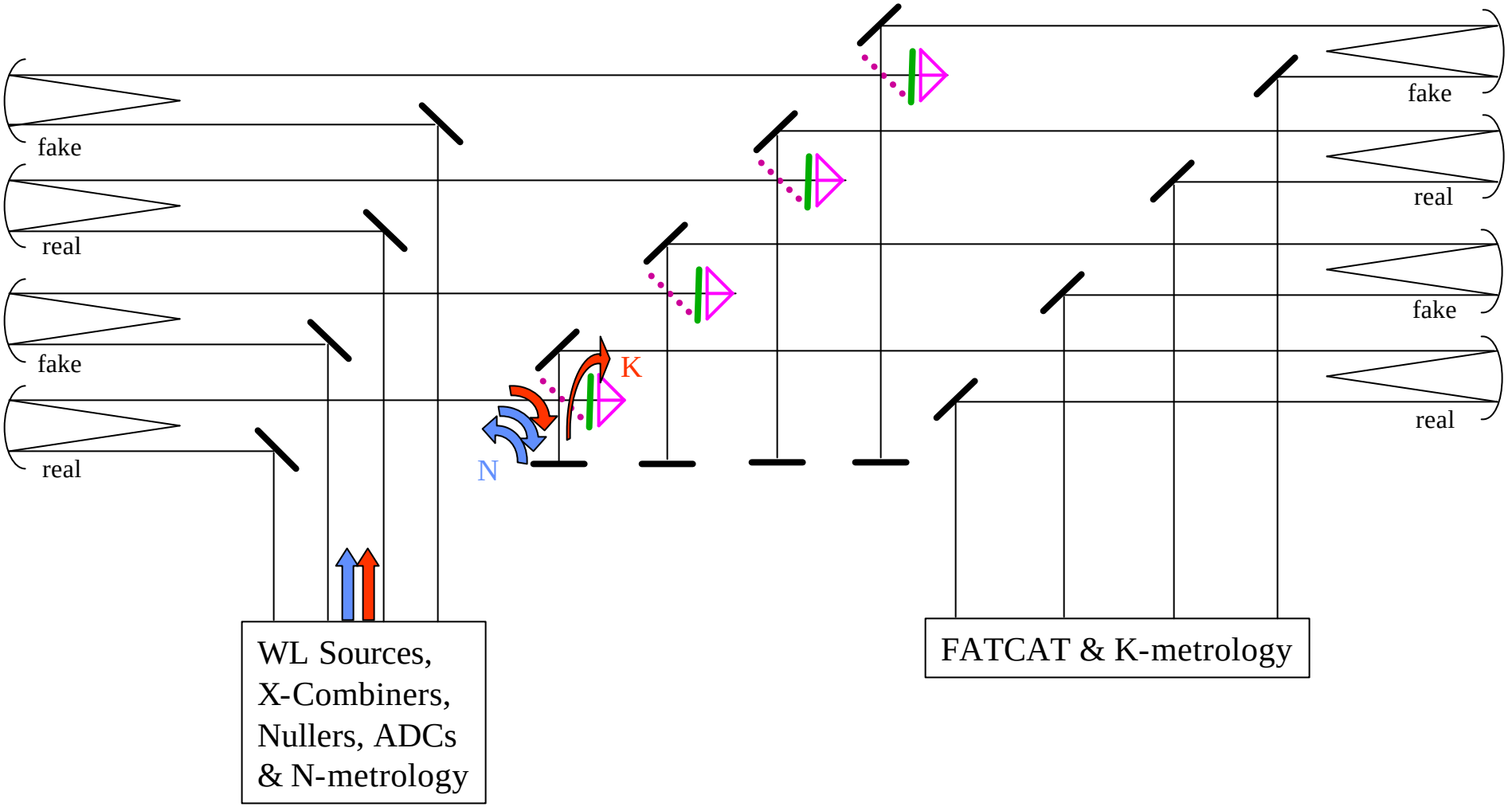
Now moving into I&T phase

MIR KALI Camera

- 4 input beams
- Cold beam apertures
- Cold Pinholes
- Pupil imaging lens
- Direct view prisms
- 128x128 detector array



Nulling I&T Lab Layout



ADCs to distort and correct phase in lab

= K/N splitters

Keck Project Status and Near-Term Schedule

– Visibility mode functional at Keck
– First pair of visibility-based astronomy papers in ApJ

– Nulling breadboard functional at JPL
– Nullers integrated with fast delay lines & switchyard optics
– Real-time software work proceeding; fringe tracker integration next
– MIR camera assembled; first camera cool-down this week
– The nuller is scheduled to ship to Keck near the end of this year

– Differential Phase next priority